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Implementing Green Infrastructure for the Spatial Planning of Peri-Urban Areas in Geneva, Switzerland

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Abstract: The concept of green infrastructure (GI) seeks to identify and prioritize areas of high ecological value for wildlife and people, to improve the integration of natural values in landscape planning decisions. In 2018, the canton of Geneva, Switzerland, established a roadmap for biodiversity conservation, which includes the operationalization of GI covering 30% of the territory by 2030. In this paper, we demonstrate a GI mapping framework in the canton of Geneva. Our approach is based on the combined assessment of three 'pillars', namely species' distribution, landscape structure and connectivity, and ecosystem services, to optimize the allocation of conservation actions using the spatial prioritization software, Zonation. The identified priority conservation areas closely overlap existing natural reserves. Including the three pillars in the landscape prioritization should also improve adhesion to the GI idea, without undermining the protection of threatened species. With regards to land use planning, public and private land parcels with high values for GI may require specific incentives to maintain their desirable characteristics, as they are more likely to be degraded than areas with more building restrictions. Visualizing priority conservation areas in a spatially explicit manner will support decision-makers in Geneva to optimally allocate limited resources for ecosystem preservation.

Keywords: spatial conservation prioritization; systematic conservation planning; environmental policy; Zonation; Biodiversity Strategy; Geneva; Switzerland

1. Introduction

Ecosystems integrity and resilience are threatened around the world by unprecedented habitat degradation and destruction by human activities, which are causing significant biodiversity losses [1,2]. Our epoch, labeled as the 'Anthropocene' [3,4], faces a triple challenge to ensure the sustainable provision of resources, the mitigation and adaptation to climate change, and the preservation of biodiversity [5]. With 68% of the world's population expected to live in cities by 2050 [6], this rapid urbanization causes major pressures on peri-urban lands and on the stability and resilience of their ecosystems.

Biodiversity hotspots, characterized by high levels of biodiversity in the form of species richness and endemism, have traditionally been proposed as a global conservation priority. Since 2010, international agreements from the Convention on Biological Diversity (CBD) require nations to restore 15% of degraded ecosystems, conserve at least 17% of terrestrial and inland water areas, and 10% of coastal and marine areas by 2020 towards the fulfillment of the Aichi biodiversity target 11 [7]. This 'land-sparing' approach could, however, create an intensification of land use outside of protected areas to meet the demands of a growing population [8].

New approaches to conservation have emerged, because biodiversity is still declining at alarming rates and land losses are increasing despite long-lasting efforts to protect species and ecosystems [9,10]. One emerging view (called "People and Nature") [11] offers a vision in which sustainable landscapes that accommodate food production and other human activities coexist with biodiversity conservation as a result of improved landscape planning. This new paradigm considers the strong interrelations between ecological and socio-economic systems and highlights our dependence upon ecosystem services. Under this view, conservation efforts emphasize the importance of optimizing the allocation of protected areas while effectively ensuring their management and allowing for other human activities such as food production, mobility, and habitation. It is unknown, however, how the resulting green infrastructure (GI) that integrates anthropocentric values captured by "ecosystem services" will differ from a "biodiversity-only" approach based on intrinsic values such as species richness, rarity, and endemism (Mace, 2014).

Indeed, the ecosystem services (ES) concept is a valuable tool to help policy makers and stakeholders adhere to ecosystem protection. By demonstrating the links between a healthy ecosystem and human wellbeing (e.g., heat island mitigation provided by tree canopy cover), people can value nature in novel ways and realize the importance of its preservation. ES can be defined as flows of material or energy from stocks of natural capital to people (Costanza et al. 1997), which may be combined with manufactured services to satisfy human needs or contribute to their wellbeing (de Groot, Wilson and Boumans 2002).

Similarly, Green Infrastructure has been suggested as a tool to support sustainable development by reconciling environmental preservation and other interests in landscape planning and management [12]. The concept of GI has been applied in planning and policy-making related to various domains including biodiversity protection [13–15], urban water management [16–18], human health and wellbeing [19–21], disaster risk reduction [22,23], and climate adaptation [24–26]. However, there are noticeable differences in its implementation depending on the context in which it is employed. Some approaches include the ecological network enabling species' movement between core habitats [27]. Others refer to urban vegetation providing ecosystem services [24,28], while still others use the concept to define engineered or semi-natural structures designed to manage storm water in a more sustainable manner [17,29].

The European Environment Agency describes GIs as a "strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services" [30]. We interpret the EEA's definition as being synonymous to the one provided by Benedict and McMahon [31] who call it the "ecological framework for environmental, social, and economic health—in short, our natural life-support system".

In a national context, the Swiss Biodiversity Strategy was introduced as a law in 2012 and developed a related action plan for its implementation in 2017 [32]. Main measures in the Biodiversity Action Plan include promoting biodiversity through the creation of GI, reinforcing collaborations between federal biodiversity policy and other policy domains, and raising awareness among stakeholders of the importance of biodiversity. Following this scheme, the canton of Geneva has published the first cantonal Biodiversity Strategy in 2018 to reinforce and implement the national biodiversity laws at local scale [33]. The objective for Geneva's Biodiversity Strategy is to reach 17% of protected surfaces within the canton, and an additional 13% of surface area compatible with providing a supporting role.

Presently, decision-makers lack a tool that translates how natural areas directly or indirectly affect the population's wellbeing, and the costs of inaction regarding ecosystem degradation. The GI offers the potential to identify the key landscape features and areas that favor the emergence of sustainable landscapes. Despite growing interests among environmental research and policy circles, the concept of GI has seldom been fully implemented in local strategies, and its application in spatial planning at all scales remains a hurdle in Switzerland. Thus, the operationalization of GI is one of the principal objectives of the Geneva Biodiversity Strategy [33] and the Confederation's Swiss Biodiversity Strategy and Action Plan [32].

A particular challenge in GI mapping and planning is to establish the GI network in areas where they effectively provide conservation benefits for both wildlife and people. Designation of GI networks has, in many cases, relied on a few selected ES and/or habitats in general, and not necessarily on a broad range of ES and representative species [34]. Consequently, GI with a limited focus may be suitable for a specific environmental purpose (e.g., storm water management or erosion control) but does not fulfill the ambition of the local and national Biodiversity Strategy to preserve the full spectrum of biodiversity and ecosystem services. In fact, while the provision of ES implies certain levels of biodiversity, ES-rich areas do not necessarily overlap biodiversity-rich areas [35]. Therefore, the priority areas for biodiversity and ES should be included as complementary conservation targets, as planning for one alone could underrepresent the other [36].

Furthermore, commonly employed methods for mapping GI including overlay analyses with Geographic Information Systems (GIS), morphological spatial pattern analysis, minimum path model, graph-based analysis, and landscape-functional units [37] are not well-suited to account for trade-offs and synergies among GI features. For such analyses, spatial conservation prioritization is widely used among conservation biologists to allocate conservation actions and protected areas [38,39]. Fundamentally, spatial prioritization software is based on computational methods to optimize the selection of priority areas in a landscape and can account for trade-offs and synergies between input features, by finding a balance between a large number of partially synergistic and partially conflicting considerations.

Many different approaches have been developed to optimize the allocation of conservation priorities, such as methods based on key biodiversity areas [40], biodiversity hotspots [41], or systematic conservation planning [42]. Spatial conservation prioritization corresponds to the technical phase of systematic conservation planning, and is typically implemented using site selection software based on optimization algorithms, such as Zonation, Marxan, and C-Plan [38].

In a recent conceptual paper (Honeck et al., in review), we proposed an approach to plan GI based on the prioritization of several pillars representing biodiversity itself, habitat structure and connectivity, and ecosystem services. With this study, we aim at demonstrating how this approach is relevant in the specific case of the biodiversity conservation strategy of a peri-urban area around Geneva using Zonation. Feature weights are attributed to influence the solution in order to account for the relative importance of factors such as species rarity, ecological connectivity, and opportunity costs. Despite being appropriate for GI network mapping, new users must overcome the effort of gathering the necessary inputs.

Our study addresses the following questions to design a GI aligned with local environmental and biodiversity strategies:

1. What is the relative influence of adding ES and landscape structure and connectivity to a biodiversity-based GI to identify high-, medium-, and low-priority areas?
2. What fraction of threatened species is covered by GI when ecosystem services, and/or landscape structure/connectivity are integrated in its definition?
3. How much of existing protected areas are covered by the GI proposed in this study?

4. What is the feasibility of the objectives of conserving 17% of protected areas and an additional 13% of GI in the Geneva context?

2. Materials and Methods

2.1. Study Location

Our study focused on the canton of Geneva, Switzerland. The territory of Geneva is characterized by a dense urban area at its center (13%), surrounded by peri-urban landscapes constituted of agricultural land (45%), forests (11%), and rivers with other natural vegetation [43]. Geneva has a very prosperous economy, which attracts many companies and people altogether. Conscious of the importance of rural areas for agriculture to produce food, but also for other natural resources, the political intent is to keep development in the urban area by densification.

Fortunately, strong legislation allows keeping housing development close to existing cities and villages. In addition, other equipment like roads are also jeopardizing the quality of the natural ecosystem. In 2018, the population in the canton of Geneva reached 500,000 people [44]. The resulting population density—2028 inhabitants per km^2 for 2018 in the canton of Geneva [45]—is generating competing interests for a limited space, as well as growing environmental pressures from urban expansion and other human activities. Identifying and making GI visible should help preserve the more sensible habitats, and simultaneously make available enjoyable spaces for human recreation available, without negatively impacting the remaining high levels of biodiversity in the canton.

In Switzerland, 12.5% of the territory is protected as natural reserves, mainly in the Alps [46]. Thus, Switzerland still lacks 4.5% of protected surfaces to fulfill its national requirements towards the Aichi Biodiversity Targets. Currently, the 10.8 km^2 of protected areas in the canton of Geneva represents 4.4% of the canton's territory (excluding the lake of Geneva) [47]. To reach the Aichi target of 17% it is therefore important to identify remaining hotspots and ecological corridors to keep the landscape functionality of the whole territory.

2.2. Study Design—Methodology Flowchart

In this paper, we present an original implementation of a "three-pillar" Green Infrastructure (Figure 1, Figure S2) defined previously (Honeck et al. in review). This approach proposed to prioritize landscape units based on the separate assessment of 1) species richness as a measure of biodiversity, 2) ecological structure and connectivity, and 3) ecosystem services. The pillars were then integrated into a spatial prioritization with the Zonation software [38]. Zonation does not simply perform the equivalent of a weighted sum, but rather computes the optimal way of covering a minimum of all features (i.e., species, habitats, ES, etc.). This method allows building GIs based on different weights of selected input features according to conservation objectives agreed upon with local stakeholders. This highlights shared opportunities to align biodiversity protection with sustainability goals.

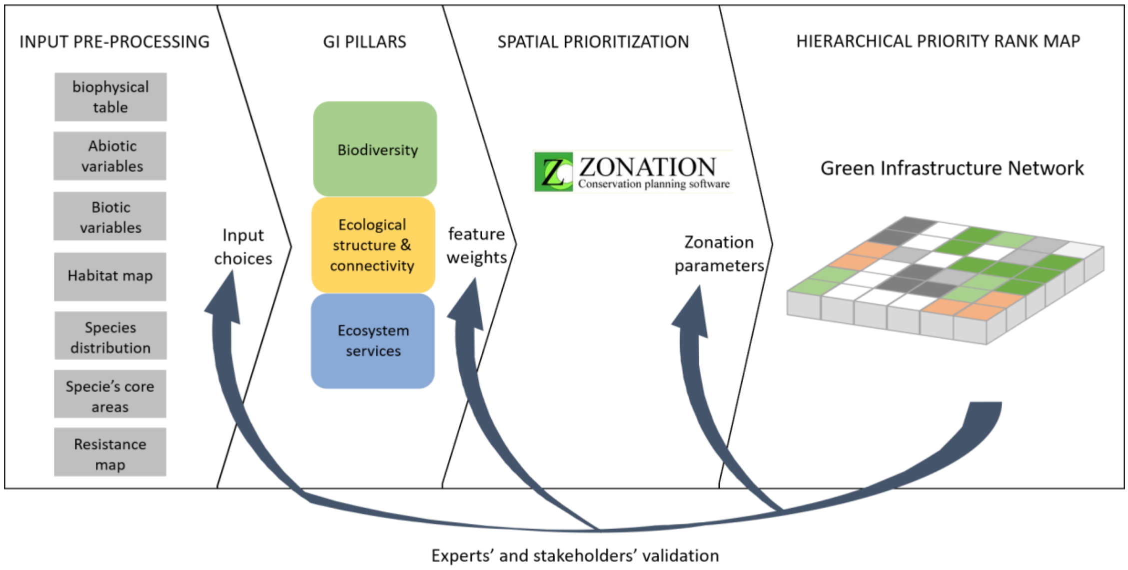

Figure 1. The three-pillar approach for mapping green infrastructure (GI).

2.3. *Spatial Conservation Prioritization*

2.3.1. General Methodology with Zonation

The Zonation software was designed to produce a hierarchical prioritization across the landscape to support ecologically based land use planning [48]. Zonation's algorithm starts from the full landscape and removes the grid cell with the smallest aggregate loss of conservation values (species habitat, ES, or connectivity) at each iteration to produce a spatial priority map ranked by the relative importance for the specific conservation objective. It is critical to this process that a balance between all input features is maintained throughout the ranking. At the end of the ranking, the top-ranked areas jointly represent a balanced coverage of features to optimize the preservation of the landscape's natural capital. Most applications of Zonation concern the evaluation of a landscape's ecological value, and the optimization of spatial conservation allocation or spatial impact avoidance by balancing multiple biodiversity features such as habitats, species, connectivity, and ecosystem services [49]. Also, costs, opportunity costs, and threats (pressures) can be integrated into the prioritization process.

2.3.2. Zonation Parameterization

We used Zonation's additive benefit function (ABF) option, which indirectly aims at minimization of extinction rates. This method implicitly favors feature-rich areas in the prioritization, due to their ability to provide coverage and protection for many biodiversity features simultaneously [49]. For questions 1 and 2, we used equal weights between pillars (Table S3), and for Geneva's GI, feature weights were attributed according to a fictive scenario established through a participatory process during a public biodiversity workshop [50] (Table S4). Official weighting of the pillars was decided later on, after a formal and representative voting process together with stakeholders, to meet local conservation objectives. Given that Geneva's GI will be used as a tool to preserve biodiversity in particular, policy makers from the cantonal office of agriculture and nature would give more weight to conventional biodiversity indexes and ecosystem structures and connectivity than to ecosystem services. In addition, red-list species were weighted twice as much as least-concerned species (occurrence areas of narrow-range species tend to become highly prioritized within Zonation even without over-weighting due to range-size rarity calculations that underlie analysis).

The lake of Geneva together with the Rhône and Arve rivers represents nearly 15% of the canton's area. Aquatic ecosystems have a different functioning altogether that would benefit from the definition of its own prioritization with a "blue" infrastructure, so we decided to exclude it from the analysis of our "green" infrastructure (although establishing a joint blue–green infrastructure in the future would be ideal). We also excluded strictly urban pixels, which were defined as fully impervious land cover as biodiversity in these urban areas is assumed to be negligible. We suggest that the promotion of biodiversity in urban areas is more related to artificial nature-based solutions than proper natural green infrastructure. We created a layer containing protected areas (meadow and dry pasture, alluvial zone, natural reserves, swamp, and amphibian breeding sites) to be able to investigate optimal expansion of the protected area set by means of spatial prioritization. As these areas are protected by federal and cantonal laws, it was justifiable to directly force them as part of the solution into the GI. However, we also ran Zonation without the protection layer to estimate how efficient existing reserves are with respect to their ability to cover biodiversity and ecosystem services.

2.4. Data Acquisition and Input Pre-Processing

All input raster data used in this study are summarized in Table S1. They were prepared with ArcGIS 10.3 [51] at a 5-m resolution, and were spatially aligned with the same extent and projection, as required by Zonation (v.4.0).

2.4.1. Natural Habitats

In 2011, the Botanical Garden, the University of Geneva, UNEP/GRID-Geneva, and the State of Geneva produced a map of natural habitats covering the entire canton. The mapping was based on aerial photography (RGB + Infrared) and Lidar data for assessing the height of vegetation. The territory was first dynamically segmented into homogeneous surfaces (with eCognition) according to the available segmentation variables (spectral, NDVI, height, etc.). Then, the probability of each type of natural habitat in every surface was modeled with statistical models (GRASP: Lehmann et al. 2012) with response variables defined with existing field data and vegetation maps, while the predictors were defined with available environmental and spectral layers. Finally, the process was completed with an expert classification tree (in eCognition) to select the most likely habitat type for each polygon. This method was partially automated to ensure timely updates when new field and cadaster data become available. This habitat map is a very valuable layer that was used as underlying input to almost every layer in the three pillars of our green infrastructure, as described next.

2.4.2. Pillar 1: Species and Habitat Diversity

Over 1,000,000 individual points of species observations are available for the Geneva area thanks to naturalist associations (*InfoSpecies* and *Faune Genève*), scientific programs, and citizens. In order to optimize the estimation of biodiversity richness, a total of 614 vascular plants species and 25 fauna species that had a minimum of 100 presence-only observations were selected to represent biodiversity in the canton of Geneva.

The first pillar on species and habitat diversity was weighted with 50% on species distribution (i.e., 25% fauna, 25% flora) and 50% habitat distribution, as they describe biodiversity at the ecosystem level and they can jointly be considered a good surrogate for biodiversity [52,53] (Table S4). Approximately 50% of animal species and 75% of plant species were classified as least concerned according to the national red list of endangered species (more details in Figure S1).

Habitat distribution:

Natural habitat is a central element to determine if a species can live or reproduce in a particular area. The habitat map was composed of 46 types of habitat. Each one was included as a separate feature in the Zonation software. We excluded non-natural types, such as roads, buildings, or impervious areas. We also created a tree density habitat layer to take into account urban microstructures that are important habitats for some species.

Flora species distribution:

We combined two datasets of plant species observations with the natural habitats map and expert knowledge on species preferences: Info Flora observations (128,335 observations >1995, with field accuracy ≤10 m) consisted of precise but spatially heterogeneous sampling points, and the atlas of flora observations (104,000 flora observations from 1990 to 2000) consisted of a low-resolution (1 km^2) but constant sampling effort over the whole territory.

We first crossed precise flora observation points with the natural habitats map to create a species—habitat matrix. This created a 1 to X natural habitat relations for each species (in % of occurrences). We then crossed this matrix with the matrix of observed species per square kilometer from the atlas. The resulting map indicated the possibility of occurrence of each species found within a specific square kilometer area, for each natural habitat polygon. The following rules were used in each square kilometer: i) Every species–habitat association above or equal to 10% was attributed to each habitat polygon; ii) if there was no species–habitat association above 10%, only the highest species–habitat relation was kept; and iii) if there was no habitat corresponding to species–habitat associations, the species was excluded from that square kilometer. This method resulted in a map with 614 vascular plants, 71 of which belonged to the red list.

Fauna species distribution:

Local experts selected 25 species, including 11 on the cantonal red list, with 100 or more observations from 2000 and 2019 (Table S2) and created a species–habitat matrix for each species. The main habitat associations for each species were used to map their possible distribution across the canton.

2.4.3. Pillar 2: Ecological Structure and Connectivity

Seven indicators were calculated to qualify ecological structure of the landscape (spatial arrangement) and connectivity for large mammals. Each input consisted of an interval of positive values, or binary values of 0 or 1.

Dark corridors:

A simple way to measure human impact on nocturnal wildlife is to consider light exposure. Based on a nocturnal aerial image of 75,000 light points combined with a viewshed analysis (ArcGIS), we estimated the coverage of visible light sources. Dark corridors were defined as pixels with no visible light [54].

Artificiality of soil:

Each habitat type was characterized as impervious or pervious, and an artificiality index was then computed using a focal statistic with a 200 m radius as follows (values were reclassified to have a minimum value of 1 in order to avoid a log of 0):

$$Artificiality\ index = Log10\ pervious - Log10\ impervious \tag{1}$$

Habitat diversity:

We conducted a Shannon diversity index with FRAGSTATS [55] in a 200 m radius, based on the natural habitats maps, to measure the potential of the territory to shelter multiple species, as well as ecosystem functions and services. The indicator shows high values when habitats are both diverse and relatively even in their frequency.

Naturality:

In order to measure habitat quality, we created a naturality index based on the urban index from O'Neill [56] as:

$$Naturality\ index = log10\ strictly\ natural - log10\ non\ natural \tag{2}$$

'Strictly natural' and 'non-natural' are 2 raster maps derived from the habitat map calculated by focal statistics in a 200 m radius. 'Strictly natural' includes habitats with minimal anthropic influence, and 'non-natural' includes urban and artificial land covers [57] (Table S5).

Mesh size:

To assess the dispersal ability of species (connectedness), we used the methodology proposed by Jaeger [58] to calculate the mesh size of a landscape in a 200-m radius. A high value indicates that the landscape is weakly fragmented and consists of large natural patches where it should be easier to move for a terrestrial taxon because of the absence of barriers, which in our study were defined as roads, buildings, and urban infrastructures or large watercourses.

Deer connectivity:

Measuring the dispersal capacity of a specific species (connectivity) is often difficult, as each species has different capacities to spread depending on factors such as organism's size, energy needs, their mobility, and barriers. Sufficient information (data observation, expert knowledge) was available for some species, including the red deer (*Cervus elaphus*), for which we created a resistance map based on the natural habitats map. The resistance value represents the difficulty to travel across a certain environment in the landscape. In the case of the red deer, these values depend on traffic load, slope, light pollution, and the presence of open environment. We then used the Circuitscape software [59], which uses algorithms from the electronic circuit theory to assess the connectivity in heterogeneous landscapes, and identified pinch points where the species has a restricted choice [60]. The "current" map resulting from this analysis was used as an input in Zonation.

General connectedness:

In order to better consider additional species, we calculated a path corridor density index in a 200 m radius (Kernel density in ArcGIS), based on the existing ecological network of the canton of Geneva [61].

2.4.4. Pillar 3: Ecosystem Services

Seven regulating services and one cultural service were selected for the GI map based on the availability and quality of the information. Several of these were mapped with the InVEST package [62]. Biophysical tables used in InVEST models can be found in Tables S5–S12.

Microclimate regulation:

Evapotranspiration and shadows provided by vegetated areas are known to create freshness islands in urban areas. LIDAR data from 2017 were used to estimate a surface model of tree canopy and define a tree shade surface as a surrogate for urban temperature regulation.

Air quality regulation:

As fine particles are filtered by vegetation, leaf area index (LAI) is a good surrogate of air regulation. We assessed LAI from Normalized Difference Vegetation Index based on Sentinel-2 images for the months of April to October between 2015 to 2018 based on the equation proposed by [63]:

$$(3)\ LAI = 0.57 * e(2.33 * NDVI) * 100 \tag{3}$$

Pollination:

Wild and managed pollinators provide a crucial service to our cultivated food crops. They require foraging and adjacent nesting habitats. We estimated the capacity of the landscape to sustain insect pollinator's foraging and nesting activities. We used the InVEST pollinator model [62] that estimates nest sites and floral resource availability within wild bee species flight ranges to derive an index of the abundance of suitable pollinator habitats on each pixel.

Erosion control:

Soil structure and quality support a range of services for natural cycles and human activities. These include dynamic life support for plants and animals, provision of resources for food production, and fundamental contributions to climate regulation and hydrological cycles. We estimated yearly sediment retention in tons per hectare with the InVEST Sediment Delivery Ratio (SDR) model [62], which maps aboveground sediment load and delivery to the stream based on topography, land use, erosivity of soils, and erodibility of rain.

Landslide protection:

Geneva is a relatively flat area with a low risk of landslides compared to mountainous regions. However, the canton is densely urbanized and requires protection in exposed areas. Swiss federal data on forests that protect from landslides, mudslides, falling rocks, and avalanches were used [64].

Flood protection:

Permeable green areas near hydrographic networks play a major role in water regulation. We derived a flood protection index by combining several layers identifying watercourses, and natural and renatured floodable areas [65–68].

Water quality:

Nutrient retention is desirable to maintain water quality and avoid freshwater eutrophication from runoffs. We used the InVEST Nutrient Delivery Ratio (SDR) model [62], which maps nutrient sources and their flow into the streams, as well as a nutrient retention index per pixel (in tons per hectare per year).

CO_2 sequestration:

To estimate macroclimate regulation, we used the InVEST Carbon Storage and Sequestration model [62], which aggregates the amount of carbon stored in aboveground biomass, belowground biomass, soil, and dead organic matter according to the land use map.

Accessibility to green areas:

Green spaces' cultural services were estimated by their accessibility. This was based on the path density 200 m around green areas, excluding roads wider than 4 m.

2.4.5. Evaluation of the Relative Influence of the Three Pillars

To create the graph representing the percentage of species and habitat distribution covered across groups of features from the respective top-priority areas (Figure 3), we first stacked all layers of flora, fauna, and habitats. Using the Raster Calculator function in ArcGIS, flora, fauna, and habitat distributions were weighted 25%, 25%, and 50% respectively, to represent biodiversity distribution in a single layer. The Zonation priority ranked map for each group of features was reclassified every 5% and multiplied with the biodiversity distribution layer. Finally, ArcGIS' Zonal Statistics function was used to calculate the percentage of biodiversity covered by each group of features for each ranking interval.

3. Results and Discussion

The inputs for the three pillars were weighted and integrated into the final GI map obtained with Zonation. The result was a priority ranking (Figure 2) that described the relative importance rank of each cell to a balanced representation of all factors included in the analysis. Colors could be adjusted to appropriately visualize priority conservation areas optimizing the preservation of the landscape's natural capital. Zonation also produced so-called performance curves that corresponded directly to the priority ranking of the same analysis. They summarized the mean conservation coverage achieved from the top-priority areas selected from the priority rank maps (Figure 6).

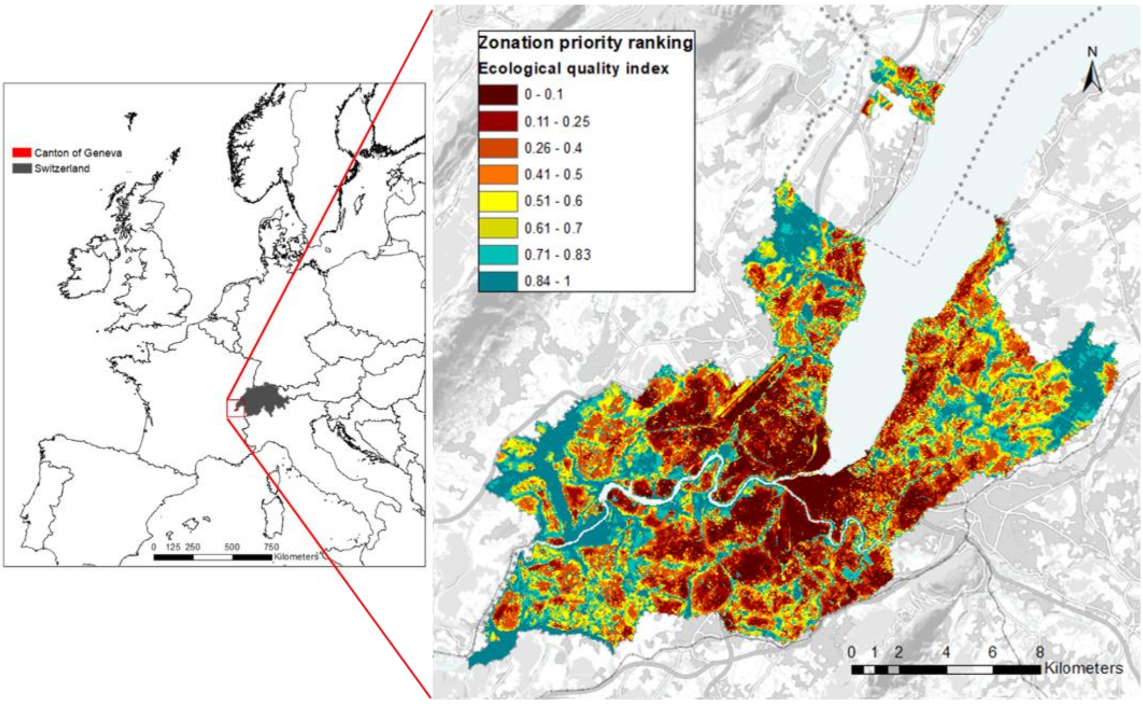

Figure 2. Hierarchical ranking of the landscape for the GI network in the canton of Geneva from Zonation's output map, with low GI values in dark red and high GI values in blue (see also Figure S3 for names and borders of communes) (background maps from SITG).

3.1. Relative Influence of the Three Pillars

To assess the relative influence of including the structure and connectivity pillar and ES pillar, we analyzed the proportion of species and habitat distribution covered across groups of features from the respective top-priority areas (Figure 3). The top 30% areas for ES alone covered 61.8% of species and habitats and identifying the top 30% areas with all three pillars combined covered 66.7% of species and habitats. The top 30% areas based on a prioritization of biodiversity pillar covered 69.6% of species and habitats (Figure 4 and Table S13).

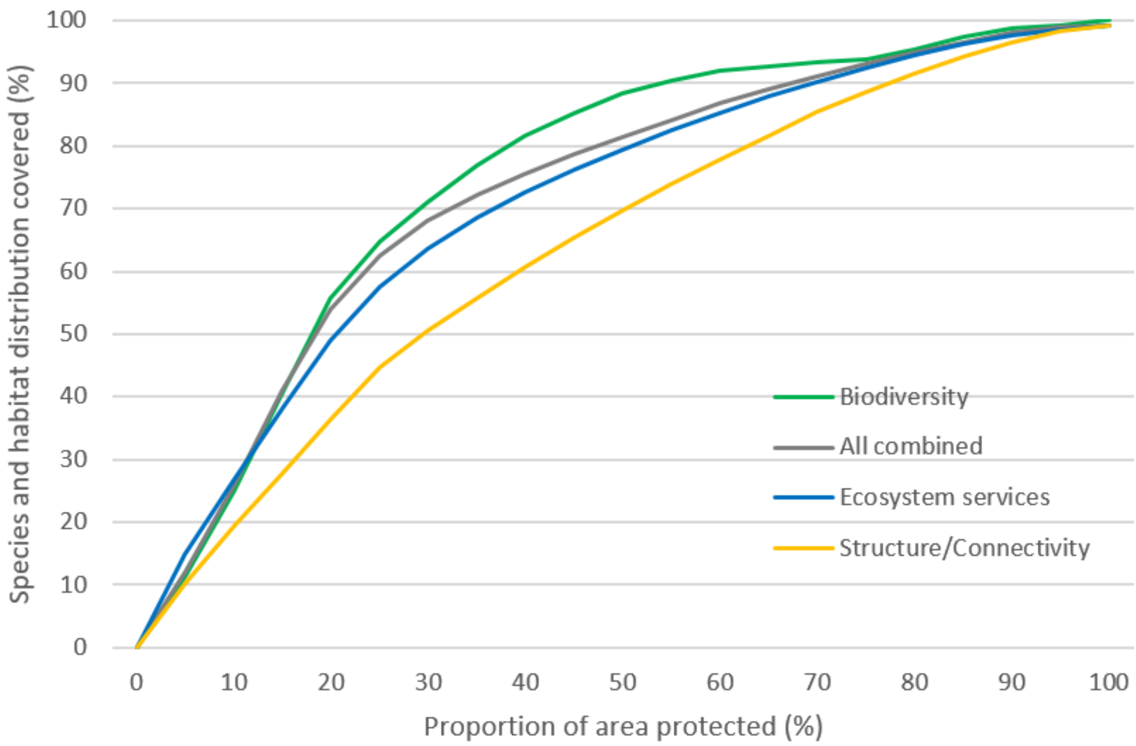

Figure 3. Species and habitat distribution covered across groups of features from the respective top-priority areas, based on Zonation's output table. This is not the performance curves output from Zonation, but a reconstructed graph.

In addition, we compared the proportion of overlapping surfaces between a GI map with the biodiversity pillar only, to a GI map with all three pillars, with structure and connectivity pillar only, and with ES pillar only (Table 1). High-, medium-, and low-priority areas were compared separately, corresponding to the best 30% (70%–100%), intermediate 30% (35%–65%), and low 30% (0%–30%), respectively, in Zonation's outputs. Equal weights were attributed to the pillars.

Table 1. Overlapping surfaces between a GI with biodiversity pillar only and a GI with other pillars.

	Biodiversity vs. 3 Pillars	Biodiversity vs. Structure/Connectivity	Biodiversity vs. ES
High priority areas	76%	50%	64%
Medium priority areas	41%	32%	42%
Low priority areas	55%	40%	57%

Seventy-six percent of high-priority areas (best 30%) for biodiversity were included in a GI based on all three pillars instead of a biodiversity-only (Table 1). Medium-priority areas were more variable, and thus had the least overlapping areas. The structure and connectivity pillar had fewer common areas with biodiversity compared to the ES pillar (Table 1, Figure 4). This seems to be coherent, as structure and connectivity represent corridors and areas linking core habitats. Virtanen et al. [69] analyzed a species versus habitats-only scenario, and showed a loss of almost half of species coverage if habitats alone were used as proxy for species and species groups.

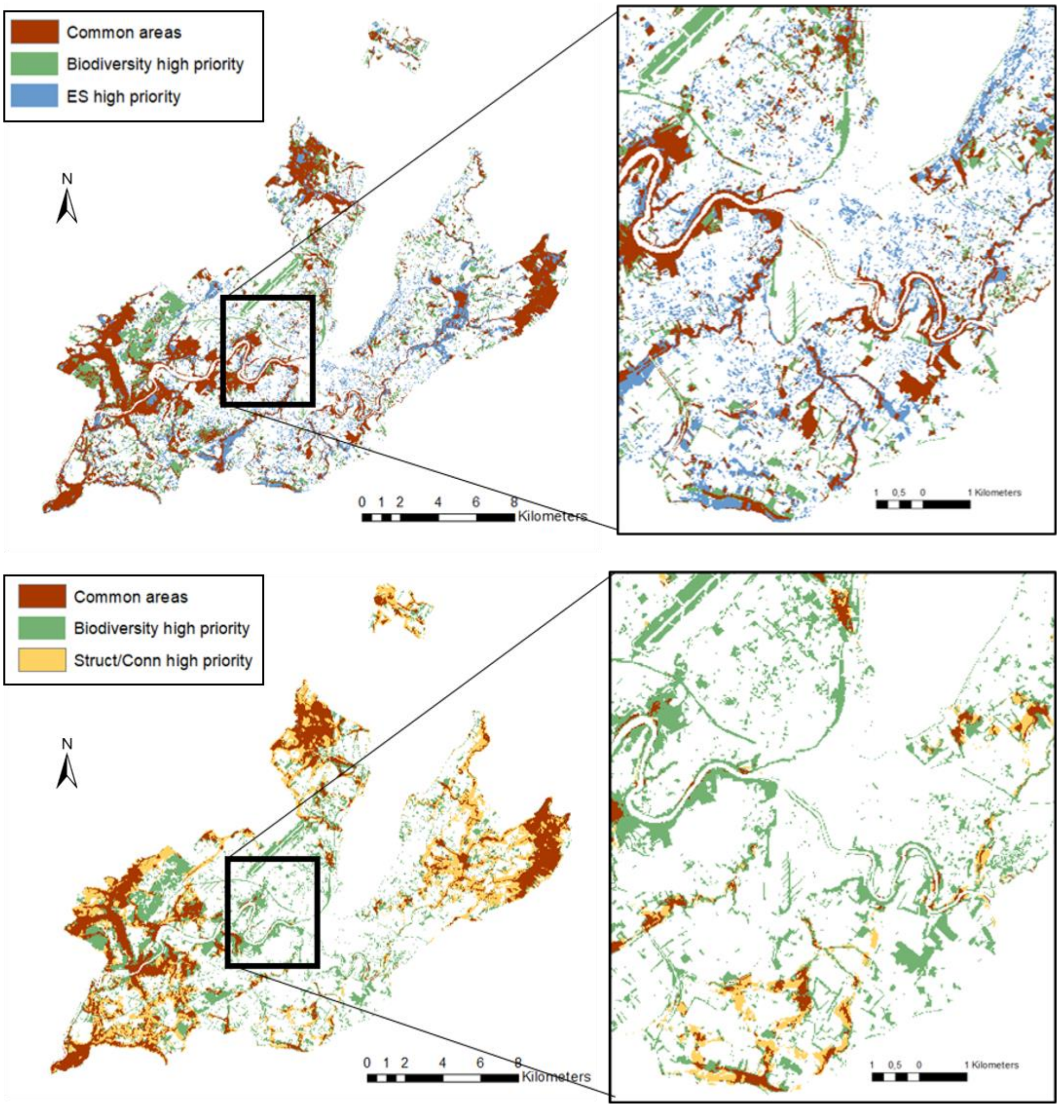

Figure 4. Overlapping areas between high-priority areas for biodiversity and ecosystem services (ES) (top), and for biodiversity and structure/connectivity (bottom), based on Zonation's hierarchical ranking map.

3.2. Occurrence of Threatened Species in GI

GI is intended to optimize the preservation of biodiversity and ecosystem functions in general, but red list species are a particular concern for Geneva's and Switzerland's Biodiversity Strategy. Some stakeholders have expressed their concern regarding the integration of landscape structure and ES in GI at the detriment of species' habitats. However, our analysis showed that the GI map designed with all three pillars was very similar to the one designed with only the biodiversity pillar, even without attributing more weight to the biodiversity pillar or to individual red list species (Figure 5). In fact, Zonation attributed higher priorities to areas for narrow-range species.

For all of the 365 red list flora species [70], their area of distribution overlapped with the top 30% conservation areas identified in both the biodiversity-only scenario and the three-pillar scenario (Figure 5). The Wilcoxon test showed that there were no significant differences in the mean of all species distributions, however, all prioritization methods also showed some outliers with low percentage of observations covered (less than 50%). Therefore, including ES in GI results did not modify the coverage of red list species, while improving the adherence to the GI concept by non-biologists. Some rare species might still need specific conservation measures beyond the creation of a GI.

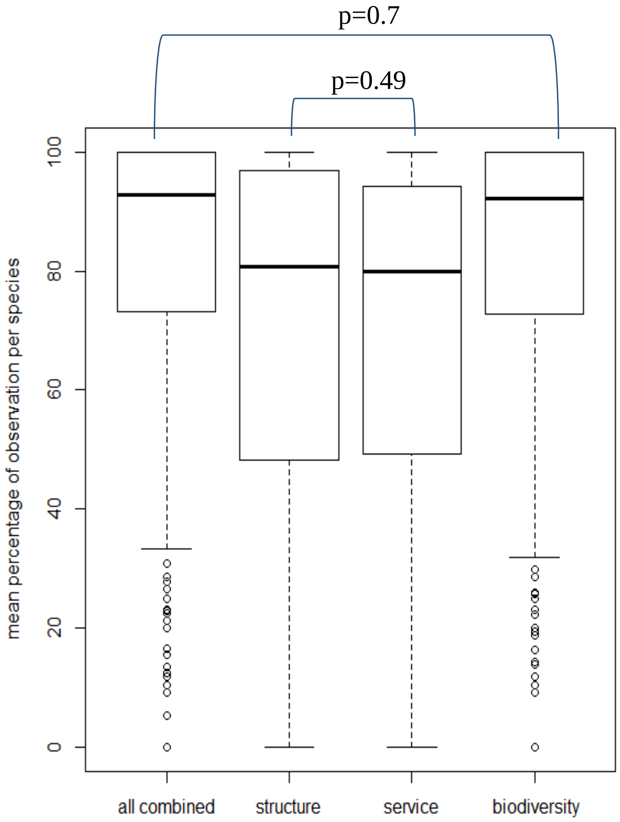

Figure 5. Mean coverage of distribution of red list species in best 30% of GI built with individual pillars, or all pillars with equal weights. P values correspond to the Wilcoxon test. The other combinations that are not indicated are significantly different.

3.3. *Efficiency of the Distribution of Existing Protected Areas*

Two Zonation analyses were performed to highlight how well existing reserves are covering existing biodiversity and ecosystem services (Figure 6). Pillar weights corresponded to the weighting scenario established for Geneva's future GI (Table S4).

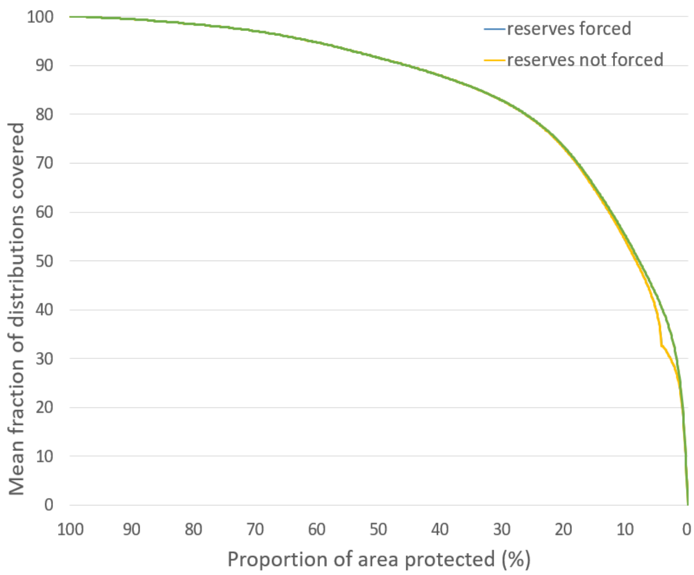

Figure 6. Zonation's performance curves of an unconstrained analysis (green) compared to a hierarchical analysis with forced inclusion of existing reserves into the top fraction (yellow).

The landscape's top 5% (in the unconstrained run) contained nearly 45% of existing natural reserves (Figure 6). Furthermore, the very shallow dent in the right panel's curve indicates that existing reserves (which represented 4% of the surface area of the canton) were relatively well located. In a Zonation analysis where protected areas were not imposed, the top 17% and 30% of the territory included, respectively, 9.1 km^2 and 10.2 km^2 of existing natural reserves (10.8 km^2).

3.4. Assessing the Feasibility of Conservation Objectives

To assess the potential pressures from other land uses, we analyzed the degree of legal protection in different zoning categories overlapping the GI map obtained with the pillar weights based on the weighting scenario established for Geneva's future GI (Table S4).

In the canton of Geneva, natural reserves, federal inventories [71], state-owned forest cadasters, and non-constructible zones around watercourses are bound with strict legal restrictions, putting them at lower risk of being developed [72] (Table 2 and Figure 7). Privately owned forest cadasters and minimum crop rotation areas [73] are also monitored and undergo regular maintenance. Building zones (state properties), roads (public domains), and privately owned parcels have fewer restrictions in terms of environmental preservation, which put areas of high ecological values in these zones at a higher risk of being degraded. Therefore, areas of the GI overlapping these high-risk zones should be particularly well communicated to landowners and stakeholders during the landscape management planning processes. Within the identified GI covering 30% of the canton of Geneva, 47.7% were in well-protected areas, and 19.7% overlap with zones with the highest risks of being degraded (Table 2).

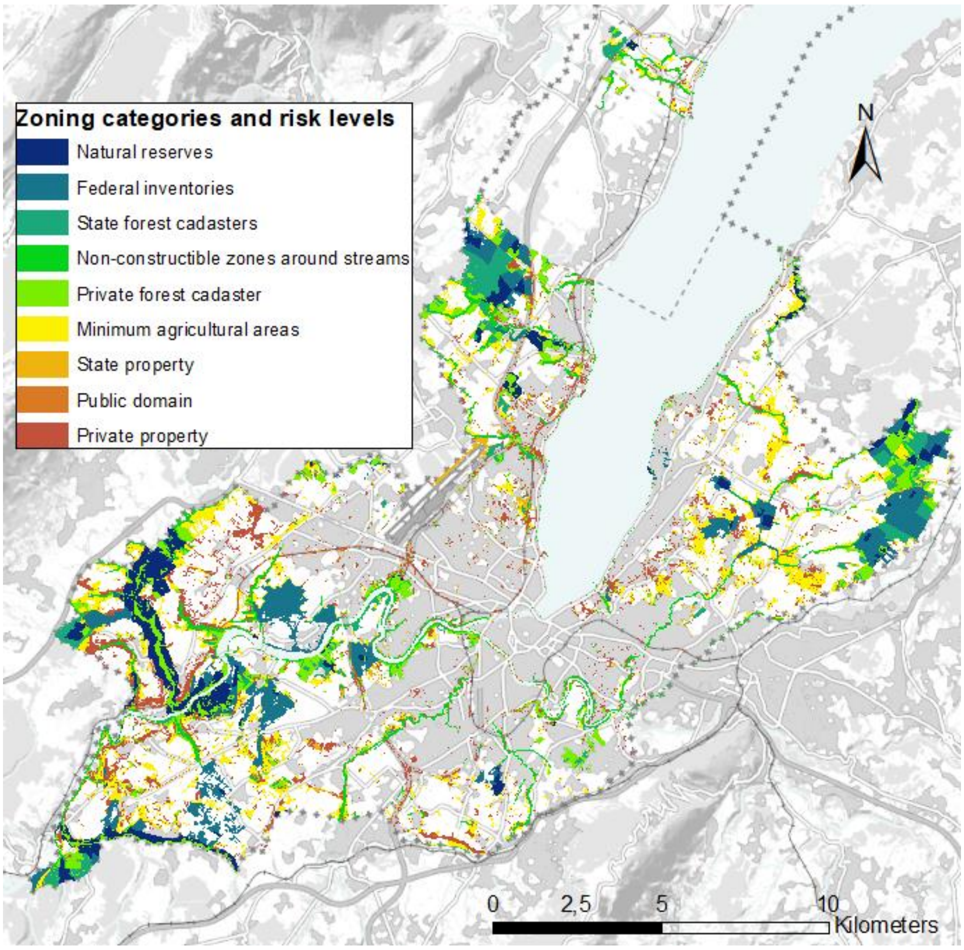

Figure 7. Assessment of potential risks of conflict in the implementation of the proposed GI representing 30% of the territory of Geneva. Risks of ecosystem degradation depend on management restrictions in each zoning category and range from low risk (blue) to high risk (red).

Table 2. Overlaps of GI areas with zoning categories and property type [47].

Risk Level		Surface in the Top 30% of the GI [km^2]	Proportion in the Top 30% of the GI [%]
1	Natural reserves	10.5	14.0
1	Federal inventories	12.0	16.0
1	state-owned forest cadasters	5.9	7.9
1	Non-constructible zones around watercourses	7.4	9.8
2	Privately-owned forest cadasters	9.8	13.1
2	Minimum crop rotation areas	14.5	19.4
3	State properties (buildings)	1.4	1.8
3	Public domains (roads)	1.6	2.1
3	Private parcels	11.8	15.8

4. Conclusions

The concept of GI is increasingly regarded as an important tool to include and enhance biodiversity and ES in spatial planning. Yet, there remains a lack of consistency in the features chosen to consider in the construction of a GI network. In this study, we demonstrate how spatial prioritization tools such as Zonation can provide a holistic view of multifunctional areas and potential conflicts. Such an integrated framework can support the assessment and design of sustainable landscape management by optimizing the spatial allocation of different management zones and helping minimize potential conflicts between environmental preservation and other land use interests.

Our evaluation of the GI network was based on an extensive amount of data on biodiversity, ecosystem services, and ecological structure of the landscape, using a well-established methodology of spatial conservation prioritization with the Zonation software [54]. We focused here on identifying priority areas in Geneva, but our approach to map GI networks could be used in any region and scale to achieve conservation objectives for biodiversity and ES. In this regard, the quality of available data on biodiversity distribution and ES is a central issue to ensure the reliability of the identified priority areas to include in the landscape planning process. In addition, our GI framework is thought to become a dynamic tool that could be used to analyze future land use scenarios.

Our main conclusions derived from the presented results are:

- The inclusion of connectivity and ecosystem services in the GI did not fundamentally modify the efficiency of the GI obtained with biodiversity only, but the resulting map is different and optimizes the cover of the three pillars. Seventy-six percent of high-priority areas (among the best 30% areas) for biodiversity is included in a GI based on all three pillars instead of biodiversity-only.
- The proposed GI with three pillars covers the distribution of red list species as well as the GI based only on biodiversity, and some rare species that are not well covered would still need specific conservation measures. For all 365 red list flora species, their area of distribution overlapped with the top 30% conservation areas identified in both the biodiversity-only scenario and the three-pillar scenario.
- Existing protected areas in the canton of Geneva are very well placed according to the GI. In a Zonation analysis where protected areas are not imposed, the top 17% and 30% of the territory include, respectively, 9.1 km^2 and 10.2 km^2 of the 10.8 km^2 of existing natural reserves.
- The feasibility of the proposed GI in the canton of Geneva is relatively high as it mainly concerns areas outside low-restriction and construction zones. Within the identified GI covering 30% of the canton of Geneva, 47.7% were located in well-protected areas, and 19.7% overlapped with zones with the highest risks of being degraded.

One of the perspectives is to include land cost and other human pressures to refine the identification of feasible conservation areas, and study how the inputs of the GI could be used to build an integrated index representing conservation absolute potential of any given area. Indeed, the result of the GI itself can only be interpreted in a relative manner, comparing the importance of each pixel relative to all others.

The GI maps produced will only indicate the expected percentage of cover of species or ES distributions and will not indicate the appropriate management method that is required in different priority areas. Expanding protected areas in a GI will, therefore, not be sufficient to safeguard the integrity of ecosystem services and biodiversity. Effective management plans with adapted restrictions must complement maps identifying priority as part of a GI network.

Top-priority areas will be distributed differently if conservation targets, such as protecting 17% of the territory (for the Aichi Biodiversity Targets), are set nationally, per canton, or municipality ('commune'). This is an important consideration, as it may influence the equal distribution of ecosystem benefits to people. Municipal authorities may also feel more motivated to invest in the protection of their own priority conservation areas that they are responsible for, rather than a portion of land contributing to conservation objectives at other scales.

Finally, this study represents a first attempt to better communicate and integrate biodiversity and ecosystem services in policy making in peri-urban areas of the canton of Geneva. This was only made possible with close collaboration and strong engagement of stakeholders from the state agency in charge of biodiversity and large consultation with stakeholders.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/4/1387/s1, Figure S1: Species number in red list classification of endangered species (A: Fauna, B: Flora). Figure S2: GI inputs and mapping flowchart. Attribution of feature weights and selection of prioritization parameters in Zonation are done through the "settings" file (in yellow). Figure S3: Zonation priority ranking (Figure 2 in article) with names and borders of communes. Table S1: Input raster data for ecosystem services. Table S2: List of selected species for the distribution of fauna. Table S3: Selected weights for each feature in Zonation for tests. Table S4: Selected weights for each feature in Zonation for Geneva's GI. Table S5: English translation of land use-land cover names used in biophysical tables, and naturality attribute. Table S6: InVEST pollination guild. Table S7: InVEST pollination land cover attribute. Table S8: Carbon pools (carbon density in aboveground biomass, belowground biomass, soil, and dead matter) for each LULC class. Table S9: InVEST NDR biophysical table. Table S10: Parameters used for InVEST NDR model. Table S11: InVEST SDR biophysical table. Table S12: Parameters used for InVEST SDR model. Table S13: The top 30% areas based on a prioritization of biodiversity pillar covered 69.6% of species and habitats. Pillars in the scenario with all pillars combined have equal weights.

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